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Optomechanical Design Of The Gun Scope Optics Using An Uncooled LWIR Thermal Imaging Sensor With A Precise Image Focusing Mechanism

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Abstract:
A well-designed optical system for a gun scope [1] needed an optomechanical enclosure to accommodate all the optical and electronic components for its required functionality and use. For this purpose, a design process was initiated considering all the optical and mechanical performance requirements of the intended product, to formulate a mechanical housing. A certain set of design steps was followed, conforming adherence to the required features and safe performance of the gun scope optics.
Gun scopes equipped with uncooled thermal imaging sensors operating in the LWIR (Long-Wave Infrared) range of 8–12 µm are advanced optical devices essential for military and law enforcement applications. These forces operate in extreme environments, from freezing mountain ranges to scorching deserts, requiring equipment that performs reliably under all conditions [2].
Optomechanical design process is quite different and challenging as compared to other conventional mechanical design processes. It involves a serious consideration of the factors, whose negligence could result in total catastrophic failure or at least a major deviation from the intended results. Use of very fine geometric tolerances and careful consideration of mechanical properties of different materials used, could only guarantee a successful designed product.
After completing a precised optical design and analysis process, its needed to formulate a suitable mechanical housing for lenses and electronics for the required functionality of the product. In this paper, all major optomechanical design steps and design considerations to be cared off, are discussed which are followed to make a successful product, complying all the requirements.
Key Words*: Thermal Imaging System, Gun Scope, Optomechanical Housing Design, SolidWorks®, Optical Drawings, Optomechanical Drawings, 3D Modeling, Material Selection, Coefficient of Thermal Expansion, Clear Aperture, Radius of Curvature, Lens Mounting, Lens Barrel, Optical Components Alignment, Element Lens Drawings, LWIR Sensor, Field of View, Focusing Mechanism, Line of Sight.*

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I. Introduction

Optomechanical designing of Optical systems is one of the most complex and difficult processes in the mechanical design field, as it involves a number of technical parameters involved at each stage. The simultaneous considerations of these technical parameters relevant to multiple disciplines need wise and deep decision-making abilities. As it involves several materials relevant to optics, metals, composites, elastomer adhesives, electronics, coatings etc., in the same structure, hence demanding a serious and deep knowledge of the mechanical, optical, chemical and electrical properties of materials used.

Well celebrated optomechanical design steps are followed to carry out design activity, to ensure acquiring true and promising results. The environmental conditions and ergonomic factors, expected to be faced by the gun user, are kept in consideration while executing the optomechanical designing. Designed for extreme conditions, these scopes deliver consistent performance in freezing mountain terrains and scorching desert landscapes, ensuring precise target detection and engagement. Their ability to operate reliably under diverse environmental challenges is essential for missions requiring precision, situational awareness, and operational effectiveness. The ruggedness and adaptability of LWIR thermal imaging Gun scopes make them indispensable tools for enhancing mission success and personnel safety in demanding conditions [2].

II. Design & Experimental Work

The optomechanical design of optical instruments is a tightly integrated process involving many technical disciplines. It begins when the requirement for a particular hardware item is established by the potential user, such as the military, other governmental organizations, or commercial representatives who seek ways to expand sales with a new or improved product. Once approved, funded, and staffed, the design effort proceeds through a logical sequence of major steps and concludes only when the instrument is awarded a pedigree establishing its ability to meet all its technical specifications and capable of being produced, within cost limits, in the required quantity [3].

The design steps followed during the entire design activity are discussed in this paper and involved:

1. Acquiring Optical Design and Relevant Data
2. Sensitivity Analysis of Optical Design
3. Defining Mechanical Requirements as per Optics' Sensitivity
4. Material Selection for all Mechanical Components and Coatings
5. CAD Modeling of all the Optics and necessary Electronics
6. Modeling the Energy Beam
7. Modeling the Enclosures
8. Defining and Modeling the Focusing Mechanism
9. Defining & Modeling Lens Mountings
10. Assembling all CAD modelled Components
11. Generate 2D Drawings for Manufacturing

The above-mentioned design steps are explained in detail below.

Acquiring Optical Design and Relevant Data:

All the optical design data is acquired from Optical Designer including in the form of Element Lens Drawings (ELDs), Air Gaps between the Lenses, Lens Materia etc. The ELDs give us information about lens overall diameter, Clear Apertures on both sides of the lens, Dia to Bevel on each side of lens, Front and Back curvature radii, Sagitta, Chamfer size, Lens Thickness, Lens Movement for focusing as given in Figure 1 below:

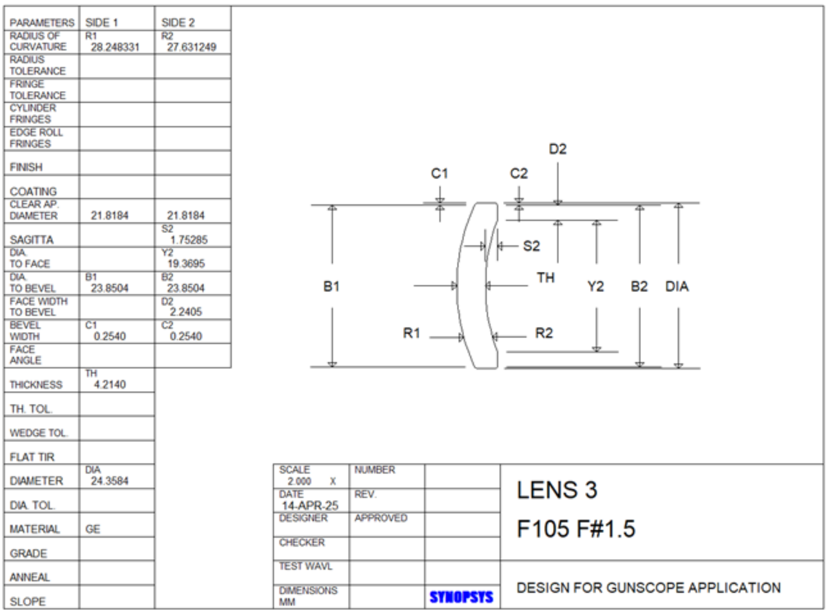

Figure 1: Template of Element Lens Drawing with Optical and Geometrical Details

Sensitivity Analysis of Optical Design:

From the ELDs, an optomechanical designer can analyze the sensitivity of Optical design and can further make a strategy on how to deal with these to achieve the desired performance of the product. Geometrical measurements of optical components, material used, shape of the edges, sagitta and tolerances, help to define a basic sketch of further design steps.

Defining Mechanical Requirements as per Optics' Sensitivity:

After studying the Element Lens Drawings, an optomechanical engineer can conclude the design approach so that the optical performance of lenses may not be compromised in static or dynamic conditions. Geometry of the lenses define a major role in lens mounting technique to be chosen, i.e., if the lens has a flat transverse surface, it can be made seated on flat metal seat touching directly with the metal surface. Whereas, for the edge to be the seating entity, there will be chosen a different mounting technique, because the edge is more sensitive to thermal expansion as compared to the flat surface of the lens. For the focusing mechanism, the lens geometry as well as the travel distance in either direction defines choice of lens movement mechanism. If the travel is longer enough, it's better to choose precised linear rails to move the lens or cluster of lenses along the axis of the optics. If the lens travel along the axis is shorter, threaded barrels can be used for the transformation of circular movement of upper barrel to achieve the linear movement of the lower barrel containing the moving optical components. This barrel design can be based upon manual rotation of barrel or motorized one, depending upon the requirements of the product performance.

Material Selection for all Mechanical Components and Coatings:

Material selection is a critical step in the optomechanical design process. Slight negligence in material selection can lead to the loss of line of sight (LOS) and can be proved to be catastrophic. The major mechanical property influencing material selection is Coefficient of Thermal Expansion (CTE). If the difference in CTEs of the mating component materials is significantly high, it may result in angular misalignment as well as the linear one. If the CTE value of one material is higher enough and the expansion process becomes active within the temperature range of the product use, it will definitely cause alignment problems. Sometimes, in an unavoidable condition, if the choice of enclosure or barrel material is limited to a specific material, and there is a chance that CTE may affect the performance, then here comes using heat resistant coatings on the external surfaces to minimize the temperature effects.

Another use of hard coatings is to reduce the friction effects between the sliding metallic parts for zooming or focusing purposes. Similar metals, such as aluminum and aluminum, should never be in contact in a threaded joint without some form of lubrication or a hard coating or plating on the mating parts because the rubbing surfaces may gall and seize. The surface preparations can significantly alter the coefficient of friction [4].

CAD Modeling of all the Optics and necessary Electronics:

CAD modeling of each component, too small it might be, including screws, washers etc., should be carried out to have a detailed picture of complete design. Based on the Element Lens Drawings, CAD models of all the optical components are made with high precision (upto third decimal fraction of a millimeter dimension). After successful modeling of lenses, an assembly file is created arranging all the components in their respective position in the optical path. The distance between each lens is kept as per the optical assembly drawing mentioning the air gaps between each lens. This air gap is the distance between the center of the curvatures, either convex or concave, of the two surfaces of the lenses facing each other. Precised positioning with the same decimal fraction is carried out to ensure the correct focal points.

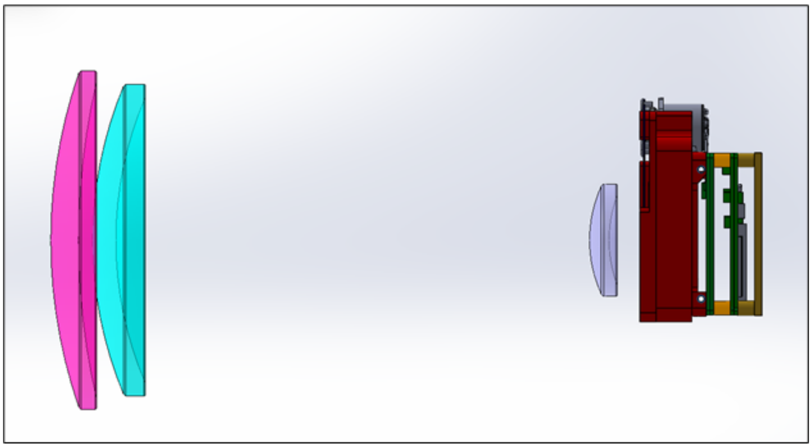

Figure 2: CAD Assembly of Gun Scope Optical Components, Sensor & Electronics

Modeling the Energy Beam:

Modeling the Energy Beam is a critical step, as it defines the periphery of the space that must not be hindered with any foreign material like metal, sealant, electronic component or wire etc. It also becomes a rationale for the geometry and form factor of the product due to being the set of coordinates defining the energy path in space. In figure 3, this is well depicted that the energy beam enters through the lens only from its clear aperture's circular boundary line, not more or not less than that; and exits through the other surface of the lens from exactly touching the boundary line of the clear aperture of that surface. This process is continued without any discontinuation till the sensor surface. As shown in Figure 3 below:

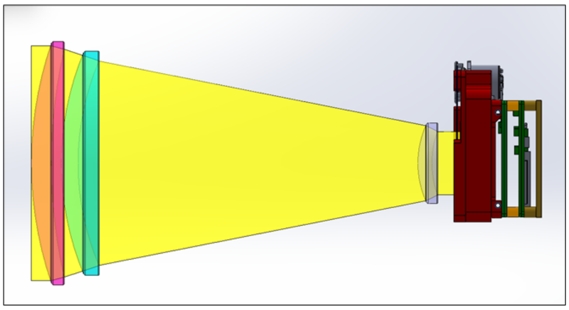

Figure 3: Modeling Energy Beam Touching the relevant Aperture Boundaries

Modeling the Enclosures:

After careful modeling of optical components, sensors, electronics and energy beam, it's time to define the lens mounting and overall enclosure of the optomechanical assembly, ultimately defining the form factor and external shape of the product. As narrated in Figure 4, the contour of the main lens barrel (colored light blue)is defined as per the slope of the energy beam, i.e., the upper surface of the beam making an angle with horizontal defining the least angle of the conical barrel. To be on the safe side, a slight gap (offset) is maintained along the convergence of the beam while defining the contour of the main barrel. Hence, care is taken throughout the design process that no material may come in the way of the beam, causing partial or total blockage of the beam. The enclosure may have some different shape as well but most of the time, free space is avoided around the optical ray path to avoid stray radiation originating from reflections form inner surfaces.

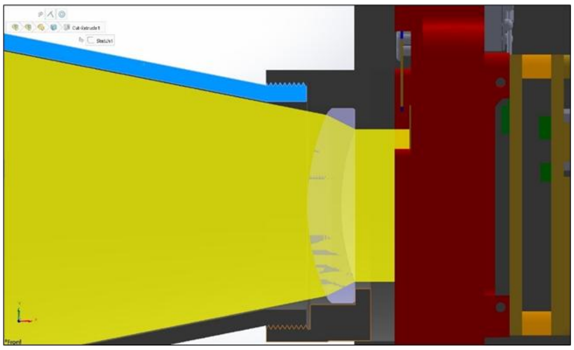

Figure 4: Modeling the Main Barrel as per Slope of Energy Beam

Defining and Modeling the Focusing Mechanism:

Choosing the right mechanism for moving a lens or a cluster of lenses in one or either direction is a quite sensitive matter. Moving an optical component needs the assurance that there must not be any misalignment either in the linear or angular directions. In case of fixed optics, it's relatively easier to control alignment, whereas in case of moving the optical components along perfectly aligned paths, it becomes quite challenging. There are many options in front of an optomechanical designer to choose for lens movement, each has its own set of advantages and disadvantages. Linear rails, motorized linear geared barrels, rotating threaded barrels etc. are some of the common focusing mechanisms used. Each has its own pros and cons and are selected based on them. We chose threaded barrel sliding mechanism that makes the moving barrel rotate and due to fine threads, slide forward or backward. The threaded barrel engagement (circled red) is shown in Figure 5 below:

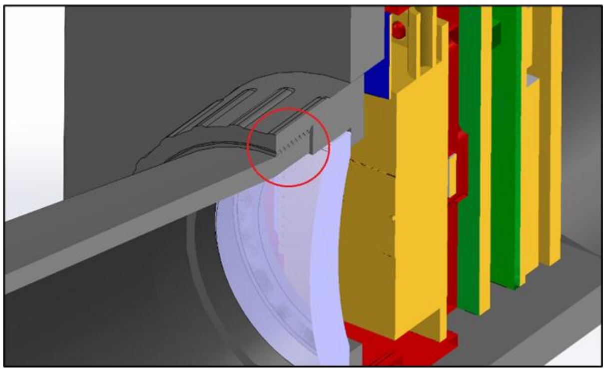

Figure 5: Threaded Barrel Focusing System for Gun Scope

As per Optical Design, at a distance of 10m, the travel of the lens for focusing, towards the sensor is 2.60 mm; whereas the maximum travel away from the sensor is 2.89 mm. Sum of these values gives us the total travel of the lens for focusing, i.e., 2.60+2.89 = 5.49 mm [2]. Thread pitch is kept very low so that after rotating the upper barrel, the linear movement of lens is less. In the focusing mechanism design, for one complete revolution of the upper barrel gives a linear distance of 0.5 mm towards or away from the sensor, depending on the direction of rotation. The thread pitch value is chosen on the basis of sensitivity of the optical design which determines how sensitive the focus is towards linear movement of the lens as narrated in Figure 6 below:

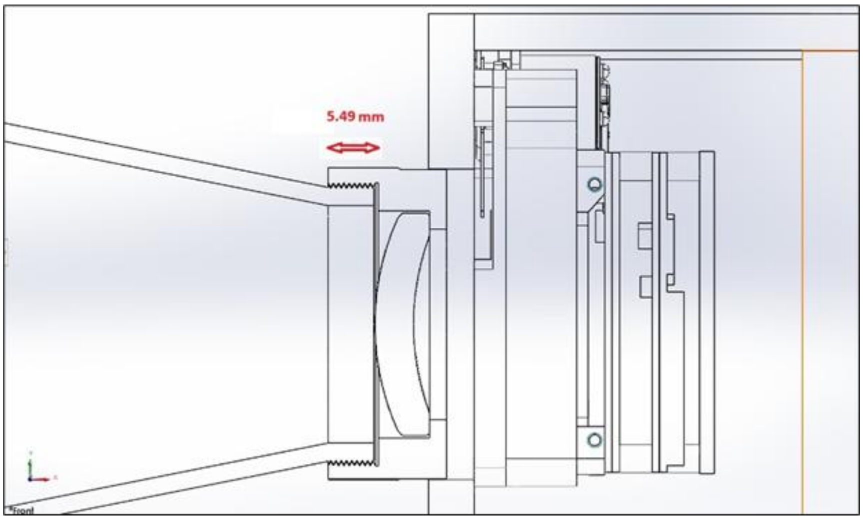

Figure 6: Total Lens Travel for Focusing, Towards and Away from Sensor

Defining and Modeling Lens Mountings:

Mounting of individual lenses depends upon many factors like, lens shape, curvature value, distance from the neighboring lens, shape of edges etc. In the present case, there is much distance among the lenses that neighboring lenses are not too close so that one may interfere with the positioning of other. Also, each lens had a flat face perpendicular to the central axis, hence giving much space to be placed on a metallic seat. So, each lens is mounted on a separate metallic seat built in the enclosure body at the inner side of the barrels. Lenses are mounted with the help of UV curable adhesives along the outer periphery of the lens.

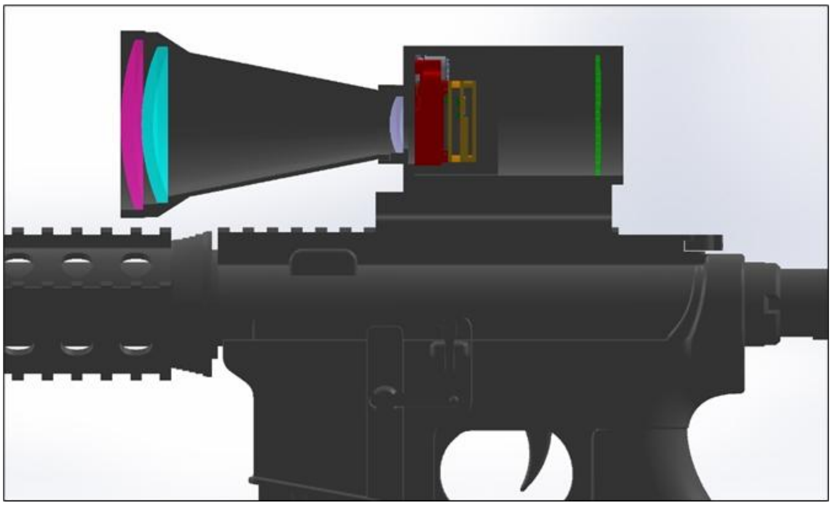

Figure 7: Lens Mounting in Gun Scope

Assembling all CAD modelled Components:

Individual CAD models of each component, either optical, mechanical or electronic; are assembled in an assembly file preserving the line of sight (LOS) of the gun. While assembling the models, one primary component is imported at the beginning of the assembly process and all subsequent parts are placed concentrically to the parent one, as shown in Figure 8 below:

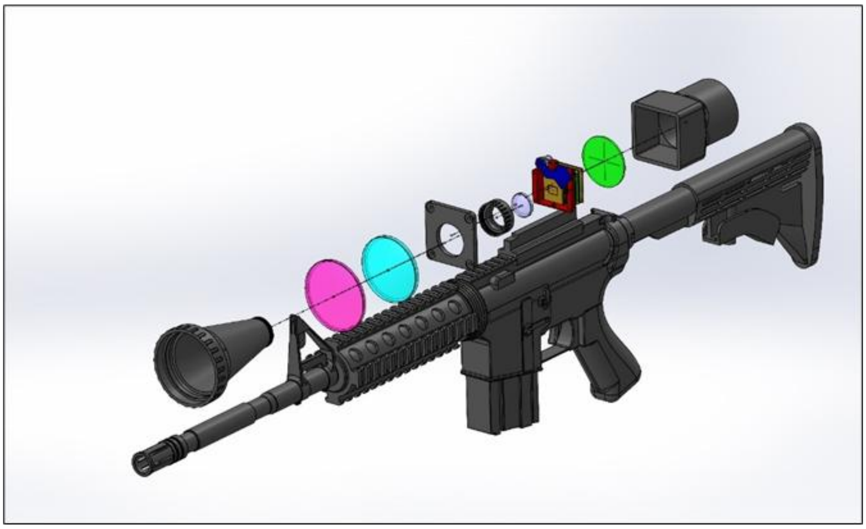

Figure 8: Disassembled View of Gun Scope and the Gun

Care must be taken while assembling the lenses, as this is the stage when there is need to keep the clearance for adhesives through which lenses are to be mounted in their respective positions. Expansion or shrinkage allowances of adhesives must be considered at this point so that during the physical assembly process, lenses may not be facing any misalignment, especially during the UV curing process. It's best practice in Optomechanics to give sprues (small holes for liquid flow) at several points, so that the push faced during adhesive expansion can be given a safe path to flow out.
An assembled view of Gun with the scope is shown in Figure 9 below:

Figure 9: Complete Assembled View of Gun Scope and the Gun

Generate 2D Drawings for Manufacturing

After completing the CAD modeling, 2D manufacturing drawings are generated. It's better to generate drawings for optical components as well, it will serve to mention some more dimensions which are not there in the optical drawings (ELDs). In mechanical part drawings, tolerances at different surfaces are mentioned depending upon the sensitivity of the mating parts. For example, tolerance at mating surface of lens and its metallic seat inside the barrel must be in accordance with the positional tolerance of that lens in optical path. A mismatch or slight negligence at these points can make the whole optomechanical design useless, as the position of the lens will be changed compared to the one specified in the optical design, ultimately disturbing the optical parameters responsible for image building and sharpness. A template for 2D drawing of optomechanical part with necessary dimensional tolerances is shown in Figure 9 below:

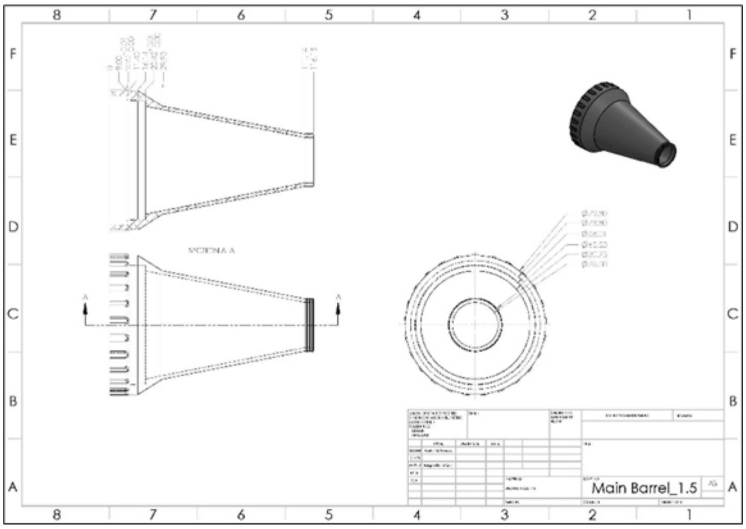

Figure 9: 2D Manufacturing Drawing of Gun Scope Main Optomechanical Barrel

III. Discussion

Optomechanical designing is way different from the conventional mechanical design process. In the paper presented, it's clear that optomechanical design solely depends upon the optical design and the promised optical specifications. The design steps explained are part and parcel of almost every optomechanical design, as it covers the basic steps needed. There can be more steps added to the list depending upon the requirements of the product and its desired performance in a specified set of environmental conditions.

Every design step has its own significance, but some of them are so critical and sensitive enough that a deep concentration must be employed while executing them, otherwise the results can be an entire failure. An expert optomechanical engineer will definitely analyze the optical design first and transform the optical design parameters into a set of mechanical ones, i.e., what are the demands of certain optical specifications towards optomechanical design and what recipe will be the most promising in terms of performance and cost.

Material Selection in optomechanical designing is very critical and strong material relevant knowledge is required by the designer in the form that he must know material properties especially thermal behavior of all the materials possibly used, as it has much potential influence in optical and mechanical performance of the product.

IV. Conclusion

The design process suggested by the known optomechanical experts, is worth being practiced, guaranteeing acquisition of best results. From understanding optical design and carrying out the sensitivity analysis of optics narrated in the optical data received by an optomechanical designer, upto the final step of generating manufacturing drawings; a deep multi-disciplinary understanding is required.

Modeling the energy beam is a significant activity, as it helps the designer throughout the optomechanical design process, to take care of the space being used by the energy beam and any inclusion of material may ruin the entire design. For more sensitive sensors, designers make the inner surfaces rough and coated by mat finished coating or paint to avoid any reflected or stray radiation interfering with the input energy.

Material Selection can turn the table to either side, i.e., complete success in performance or total catastrophic results. For our case, Aluminum 6061-T6 is used because its much stable towards temperature gradients and has a smaller value of coefficient of thermal expansion. Its CTE is just 23.6 micrometer per meter per degree Celsius is quite suitable for optomechanical designing. Also, its increased strength due to heat treatment gives the optomechanical parts with great confidence towards sudden drop or fatigue loading due to vibration.

Selection of the focusing mechanism is situation based, and the right choice mainly depends on required optical performance, ease of use, and cost effectiveness. Most common is thread-based rotation, further converting into linear movement, because it gives designers the liberty to control input rotation for the desired optical sensitivity. Using this method can give even micro-level linear movement of lenses but requires quite precision manufacturing processes involved for making fine threads.

Choosing the right and optimized lens mounting technique depends upon the shape of lenses, curvature of both lens surfaces, lens thickness, sagitta, air gap between the lenses, and many others. We chose the application of elastomer adhesive for mounting the lenses in barrels because the inner shape of the barrel had gradually decreasing step diameters of optical components and overall number of lenses was less.

All mechanically sensitive areas in the parts are provided with tight tolerances to ensure the optical lenses are seated in the positions intended by the optical designer. These tolerances are specified in the final 2D manufacturing drawings.

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